A Spectral Shallow-Water Wave Model with Nonlinear Energy- and Phase-Evolution

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LONG-TERM GOALS

Our long-term goal is to provide the international community with the capability to determine the hydro-dynamic regimes of coastal environments (including large-scale catastrophic floodings) at the highest level, both operationally, with open source computer codes supported in the public domain, and scientifically with experimental open source codes.

OBJECTIVES

Numerical wave modeling in *oceanic* and *coastal* waters is usually based on a phase-averaged approach (spectral models), whereas close to *shore*, in the *surf zone* and in *harbors*, it is usually based on a phase-resolving approach (time domain models). Both approaches can be formulated in terms of the energy and phase spectrum of the waves. In the present project we are developing a model in which both these spectra are computed simultaneously in one model set-up over a wide variety of scales (from the deep ocean to small-scale coastal regions).

Implemented on an unstructured geographical grid covering all scales (to allow the required extreme flexibility in spatial resolution), this allows waves to propagate from the ocean, across the shelf into coastal waters, around islands, across tidal flats, through channels and over shoals, into the surf zone and into harbors, but also towards cliffs and into fjords, while fully and simultaneously accounting for all relevant processes of propagation (shoaling, refraction, diffraction, transmission and reflection), generation (by wind), dissipation (white-capping, depth-induced breaking and bottom friction) and wave-wave interaction (triad and quadruplet).

APPROACH

Our approach is (a) to develop a version of our existing 3rd-generation spectral energy wave model (SWAN) on an unstructured grid and to fully integrate this version with the ADCIRC circulation model (of Notre Dame University). This allows two-way interactions between waves, wind, currents and sea level variations. The unstructured grid is common to both models, with interactions between

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the two models passing through this grid (the up-grading of the circulation model and its coupling with the wave model is addressed in a separate, ONR funded, project) and (b) to expand the energy-based wave model with a phase-evolution wave model. The technique for the latter is essentially to simultaneously evaluate a coupled set of equations**:** a spectral *energy* balance equation (already established, except for the coupling terms) and a spectral *phase* evolution equation (to be developed) on the unstructured grid. This grid is coarse where energy and phase vary smoothly (ocean and shelf sea) and fine where energy and phase vary rapidly (islands, coastal waters, obstacles, surf zone and harbor).

Leo H. Holthuijsen	Principal investigator. Associate professor at Delft University. Formulates the basic problem and approach and supervises all activities in this study. He is one of the original authors of the spectral energy model that is used in this study (SWAN).
Guus S. Stelling	Co-principal investigator. Full professor at Delft University. Supervises the development of the numerical techniques and the overall progress. Responsible for awarding Ph.D. degree to P. van Slingerland (see below).
Marcel Zijlema	Associate professor at Delft University. Develops and implements the information technology, in particular for the unstructured grid and the coupling between the wave model and the circulation model. Supports the development and implementation of the numerical methods. Releases the final products in the public domain.
Nico Booij	Associate professor at Delft University (retired). External advisor (in a private capacity; the lead author of the present SWAN model) to support both the numerical methods and representations of physical processes involved.
Paulien van Slingerland	Ph.D. student with M.Sc. degree in mathematics (Delft University). Develops, implements and tests the phase wave model and the coupling with the energy wave model. Supports the coupling of the unstructured wave energy model to the ADCIRC circulation model.

WORK COMPLETED

The basic (transport) equation for the phase model has been formulated (some source terms to be developed later). The options for the unstructured-grid formulation have been analysed and one option has been coded and is being tested.

RESULTS

The SWAN wave energy model has now been extended with the new capability of computations on an unstructured grid (SWAN^{US}). This permits computations with extreme variation of geographic resolution in one model set-up (e.g., 100 km in the ocean and – in the same model - 10 m near-shore) while retaining the implicit character of the wave model (i.e., the model in inherently stable and increments in space and time are mutually independent, allowing feasible near-shore computations). The use of an edge-based technique (as used here) for the unstructured-grid computations reduces computational times by a factor 2 as compared to using a vertex-based technique (used in some other unstructured-grid wave models).

southern North Sea

Schiermonnikoog

Ameland

north coast of The Netherlands
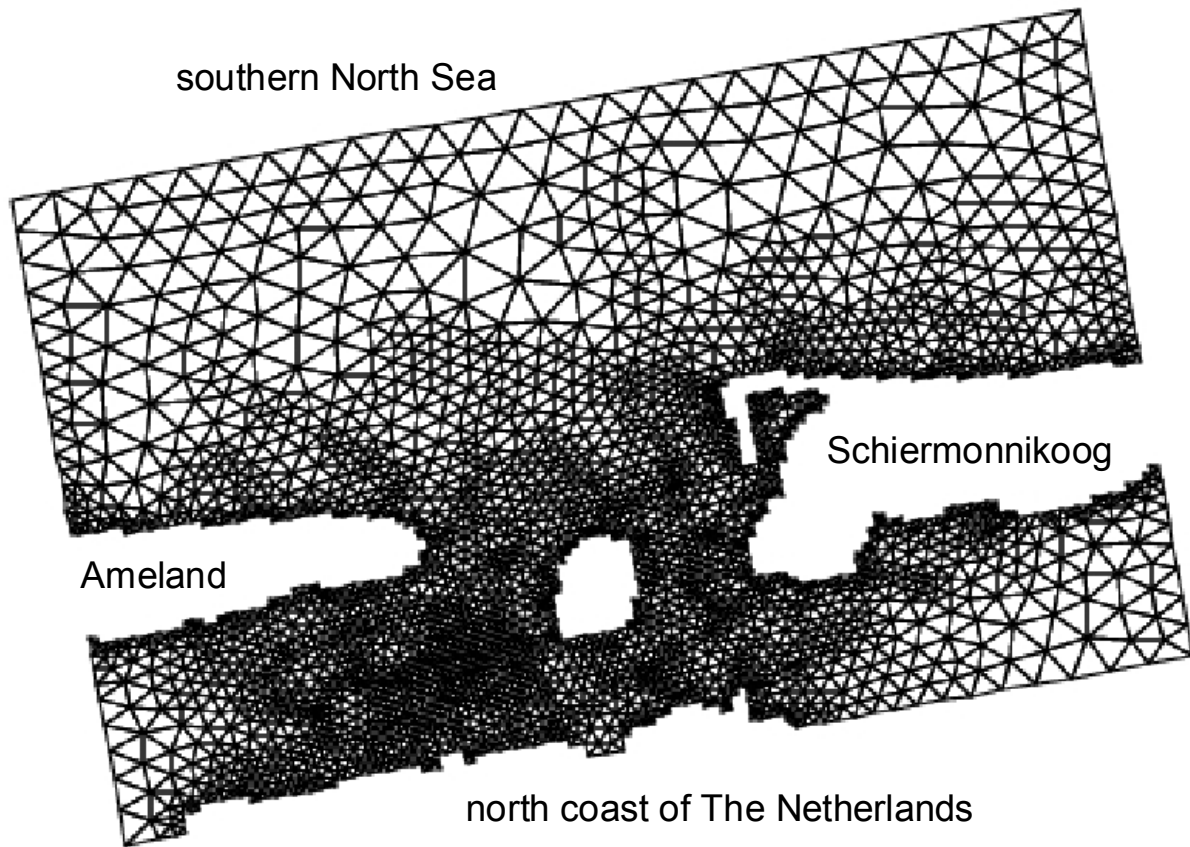
The wave model SWAN now accommodates computations on unstructured grids as shown here for the barrier islands in the north of The Netherlands.

IMPACT/APPLICATIONS

If successful, the potential future impact of the full wave model (i.e., on an unstructured grid and with phase evolution, SWAN$^{\varphi\text{-US}}$ = Simulating WAves Near-shore / phases-included / unstructured) would be to improve the quality and the operational handling of wave modeling at all scales from oceanic waters to small-scale coastal regions, surf-zones, cliffs and harbors. SWAN$^{\varphi\text{-US}}$ would not only have superior performance in *present* applications in which 3rd-generation and Boussinesq model capabilities are needed in combination, but also great potential for *new* applications. For instance, (future) data-adaptive unstructured grids would allow a detailed representation of small, moving atmospheric or oceanic driving forces such as hurricanes or oceanic rings. Adaptive grids would also allow high-resolution wave computations near a stationary or moving target such as a bay or an individual ship. Independent of such adaptive grids, SWAN$^{\varphi\text{-US}}$ would also have the potential to simulate actual surface elevations, i.e., realizations of large numbers of individual waves; in time and space, including highly nonlinear phenomena such as breaking waves (surf-zone) and freak waves (open ocean).

The coupling with circulation models such as the ADCIRC model in the present effort is equally to improve the quality and the operational handling of circulation modeling at all scales from oceanic

waters to small-scale coastal regions (joint effort with Notre Dame University). The combination would provide accurate computations of large-scale catastrophic floodings.

TRANSITIONS

The development of SWAN$^{\varphi}$-US is aimed at acquiring a numerical wave model that provides a first step towards an operationally more accurate and user-friendly platform than the present combination of different wave models that is used for wave predictions in coastal regions.

The task of developing this SWAN version on an unstructured will be carried out in close cooperation with scientists and engineers from the Notre Dame University who will couple SWAN[US] (no phases included) to their hydrodynamic model (ADCIRC) to better predict storm surges (see parallel study funded by ONR**:** Wave and circulation prediction on unstructured grids, by J. J. Westerink, University of Notre Dame, C. Dawson, University of Texas at Austin and R.A. Luettich, University of North Carolina at Chapel Hill). Delft University will advise and assist these scientists and engineers in their task to achieve this.

Both the intermediate product SWAN[US] and the final product SWAN$^{\varphi}$-US will be released in the public domain on the dedicated SWAN web site of the Delft University of Technology so that both models will be available to private industry, universities and government agencies. This is a position similar to than of the present version of SWAN with several hundred active users, except that the code of SWAN$^{\varphi}$-US will be explicitly denoted as experimental.

RELATED PROJECTS

The present operational version of the SWAN model has been developed by the same group of the Delft University that is carrying out the present project, with the active support of ONR and the Dutch Ministry of Public Works. The Ministry continues to financially support the development, management and maintenance of the public domain SWAN at the Delft University and at other institutes of research and development. The circulation model to be coupled to the new model SWAN[US] is the ADCIRC model of Notre Dame University (USA) which will be up-graded in a parallel ONR funded project (Wave and circulation prediction on unstructured grids, by J. J. Westerink, University of Notre Dame,
C. Dawson, University of Texas at Austin and R.A. Luettich, University of North Carolina at Chapel Hill).
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